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EXPERIMENTAL STUDY OF GAS KINETICS OF A FAST-AXIAL FLOW KILOWATT CO_2 LASER

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Abstract: The paper describes the rapid flow of a gas mixture in a fast-axial flow kilowatt level CO_2 laser. A high-flow-velocity wind tunnel is introduced. Gas pressure, gas flow velocity, and its method of measurement are analyzed. A wind tunnel was constructed and gas experiments were conducted. The gas flow velocity was as high as the speed of sound. Experimental data are given.

Worldwide, it is accepted that the kilowatt level, fast-axial-flow CO_2 lasers are an ideal light source, with high efficiency and good quality of light beam for high-power laser industrial processing. Within the range of 1 and 3kW abroad, these lasers have replaced most lateral-direction flow and slow-speed axial-flow devices. In China, the study of these devices is just beginning with this experiment. The article presents the results of experimental studies of gasdynamics of a kilowatt-level, fast-axial-flow CO_2 laser.

I. Introduction

The main feature of the fast-axial-flow CO_2 laser as distinguished from the stationary closed lateral-direction flow CO_2 lasers is the mode of gas flow. However, the main feature

that is distinguishing from the slow-speed axial-direction flow CO_2 laser is the gas flow velocity. Actually, a fast axial-flow CO_2 laser is a high-speed wind tunnel in the aerodynamic experiments before voltage was applied. To obtain a stable high-power laser output with good quality light beam, it is necessary to clarify the gasdynamic problems of the fast-axial-flow CO_2 laser, and to build a simulated high-speed wind tunnel for experimental studies.

Gasdynamic Problems in Fast-Axial-Flow CO_2 Lasers

1. Gas flow velocity

As pointed out by De Maria, waste heat is released from gas (electric) discharges in order to achieve fast flows of CO_2 and mixed gases in a device, thus promoting the emptying of the 100 to 020 energy levels of CO_2, and favoring the formation of reverse-rotation particle numbers between 001 and 100, in order to strengthen radiation intensity of a 10.6 micrometer laser (refer to Fig. 1). Through the dual-energy level, De Maria obtained the following:

$$\frac{P_{(\text{当}v_F \to \infty)}}{P_{(\text{当}v_F \to 0)}} = \frac{E_2 + E_1}{2E_F}\left(\frac{1 + \sigma I / E_2 + E_1 / h\nu}{1 + 2\sigma T' / E_F / h\nu}\right) \tag{1}$$

In the equation, P is the maximum density of extractive power

v_F is the gas flow velocity

E_1, E_2 are collision times of relaxation

σ is the excited emission cross section

I is the laser beam intensity

$h\nu$ is photon energy

E_F is the time of X/V_F gas flowing through the discharge zone

x is the geometric length of the gas flowing through the discharge zone

From Eq. (1), the ratio of the maximum extractive power density

increases linearly with the gas flow velocity in a resonant cavity design assuming an optimal gas compounding ratio and maximum gas flow velocity.

As revealed by further analysis, to increase the laser power of a device the time spent by the gas in flowing through the discharge zone should be reduced. Since the passage that the gas flows through in a fast-axial-flow device is much longer than the path covered by the gas in a lateral-flow, therefore the gas

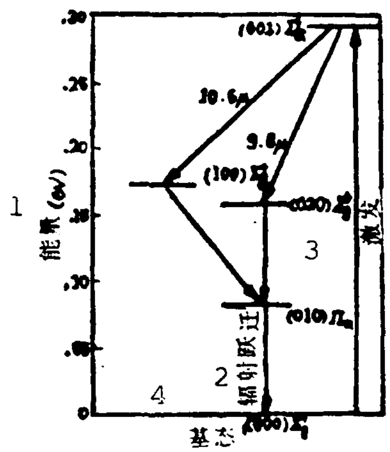

Fig. 1. Partial vibrational energy level diagram of CO_2 molecules
KEY: 1 - Energy amount 2 - Radiation transition 3 - Excitation 4 - Ground state

velocity in fast-axial-flow devices is much higher than in lateral-flow devices. In the latter case, the velocity is generally 70m/s; however, in the former case it is generally 200m/s, and even as high as 300m/s.

As the gas flow velocity is increased and becomes even higher than the speed of sound, in addition to the generation of a considerable amount of eddy current as the laser gas imposed voltage addition devices is of turbulent flow regime; this can

compel the combination of electrons or ions and neutral molecules dissipating the locally concentrated electric energy, thus avoiding arcing, so that the device operates in a glow discharge zone, thus obtaining steady laser output.

From the foregoing, the gas flow velocity is one of the most important parameters of fast-axial-flow CO_2 lasers.

How can the gas flow velocity be measured? It is very difficult to directly measure this parameter in high-speed gas flows. From the principles of aerodynamics, first measure, separately, the total pressure intensity P_{total} and static pressure P_{static} of the flowing gas. Then, according to the following formula,

$$M=\sqrt{\frac{2}{K-1}\left[\left(\frac{P_{总}}{P_{静}}\right)^{\frac{k-1}{k}}\right]} \quad [2] \qquad (2)$$

[the Chinese character in the numerator of the equation means "total", while the Chinese character in the denominator means "static".]

To derive the Mach number, the following is done: in the formula K is the adiabatic index of the gas. The gas flow velocity is:

$$V=Ma \qquad (3)$$

In the equation, a is the local speed of sound in the gas.

$$a=\sqrt{kgRT} \qquad (4)$$

In the equation, g is acceleration due to gravity, g=9.81 m/s^2
R is the gas constant, R=29.27kgm/kg-deg
T is the absolute gas temperature
k is the adiabatic index of the gas

2. Gas pressure

When satisfying the condition E/N=$2\cdot10^{-16}$x cm^2 (that is, E/P=6x torr^{-1} cm^{-1}), most energy excited by a gas (electric) discharge is converted into the excitation energy of CO_2

molecules 001 and N_2 molecules V=1 to 8 vibrational energy levels. At this time, the quantum efficiency of the laser is also as high as 41 percent; the output power of the laser is the highest. The fast-axial-flow CO_2 laser also should satisfy the above-mentioned working conditions. After the device (electric) discharge status is determined, there is an optimal gas filling pressure range corresponding to the optimal device output. The optimal pressure is determined through trial and error.

2. High-velocity wind tunnel

As mentioned above, a fast-axial-flow CO_2 laser corresponds to a high-speed wind tunnel. For a transonic speed wind tunnel, the gas flow velocity M=0.8 to 1.2, or for a supersonic wind tunnel, M=1.4 to 4.5. These are called high-speed wind tunnels. However, the lateral-flow device also corresponds to a wind tunnel; only its flow velocity is 70m/s, corresponding to a low-speed wind tunnel.

Generally, a wind tunnel is composed of four portions: convergent section, experimental section, divergent section, and drive equipment. The experimental section is the (electric) discharge tube of the fast-axial-flow CO_2 laser. However, the convergent and divergent sections are structures that should be installed for the gas passing through an isentropic, adiabatic expansion so that the velocity changes from low to high speed, and then changes back to low speed. If the convergent section throttle is the first throttle, then the divergent section throttle is the second throttle. The ratio of the cross-sectional areas of the two throttles should satisfy the following diagram.

The drive equipment is the source of gas flow energy. In fast-axial-flow CO_2 lasers, generally mechanical pressure booster

pump is used; or, an axial-flow air blower is used, in some cases.

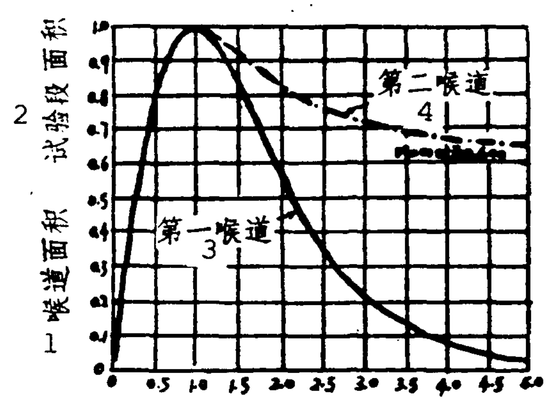

Fig. 2. Relative area ratio of first throttle and the maximum relative area ratio of second throttle
KEY: 1 - Throttle area 2 - Area of experimental section 3 - First throttle 4 - Second throttle

Experiments and Data from High-Speed Wind Tunnels

Fig. 3 shows a high-speed wind tunnel experimental installation built by the authors. The operational section is made of glass. Since the optical cavity of a kilowatt-level fast-axial-flow CO_2 laser is folded from model ╤ with a total of four (electric) discharge tubes, therefore the authors combined the four tubes into an experimental section with equal lateral cross-sectional area. To change the gas flow velocity in the experimental section, the authors designed the lateral cross-sectional area of the convergent section into variable types by adjusting the gap of the ring-shaped nozzle with two threads. In the experimental sections of the wind tunnel, a total pressure determination tube was installed in each section; these are the Pitot tube and the static pressure determination tube made of

stainless tubing with OD1mm and wall thickness 0.2mm. It was required that the tube opening of the Pitot tube be strictly vertical to the gas flow direction. For model ZJ-1200 mechanical pressure booster pump with a suction rate of 1200liters/s, the magnitude of the suction rate is determined by the laser power. At the exit of the mechanical pressure booster pump, a heat dissipation unit was connected in order to eliminate the temperature rise caused by the pump compressed gas. At the pump inlet, and between the pump and the heat dissipator, a pressure-measuring core was installed at each site to connect a mercury U-type *manometer* to measure the gas pressure.

During experimentation, air was used as the test medium. At different gas filling pressures, adjust the nozzle spacing in order to measure P_{total}, P_{static}, P_{inlet}, and P_{exit} of the high-speed gas flow, as well as the input power to the pump. The

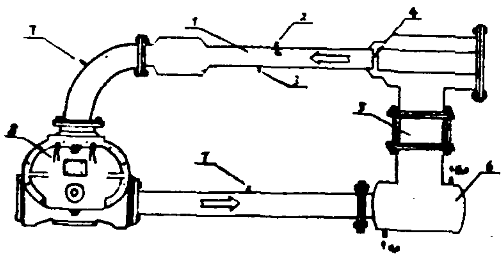

Fig. 3. Brief diagram of experimental installation of kilowatt-stage fast-axial-flow CO_2 laser high-speed wind tunnel
Remark: 1 - Discharge operational zone (experimental section) 2 - Total pressure determination tube (Pitot tube) 3 - Static pressure determination tube 4 - Ring-shaped nozzle 5 - Corrugated tube 6 - Heat exchanger 7 - Gas pressure determination tube 8 - Model ZJ-1200 mechanical pressure booster pump

Mach number of the gas was calculated from the measured data, $\Delta P(\Delta P=P_{inlet}-P_{exit})$, and $\eta(\eta=\Delta P_{exit}/P_{inlet})$. As listed in Table 1, all the instruments used are as follows: two sets of model HL23/1 current inducer with 0.2 precision level, two D26-W

wattmeters with precision of 0.5 level, model 95 semiconductor spot thermometer and a U-type mercury vacuum gauge (with a total of four meters). The ambient temperature during experimentation was 3 to 9°C; gas pressure was between 765 to 773mm of Hg column; and cooling water temperature was 22°C.

Sources of errors: 1) the entrance of the Pitot tube is not strictly perpendicular to the direction of gas flow so that the total pressure reading is understated, that is, the M number is understated. 2) Reading error of the U-type manometer.

Finally, experiments for the maximum compression ratio of the ZJ-1200 pump were carried out to measure the noise, with the data listed in Table 2.

Discussion

1. This experiment obtained high-speed and stable gas flow. Assume that the gas temperature is 25°C in the experimental section, T=298°C. These figures are inserted into Eq. (4),

$$a=\sqrt{kgRT}=346m/s$$

By taking the mean value from the measured Mach number, with calculations based on M=0.8, the gas flow velocity in the experimental section can be obtained, as:

$$V=aM=346\times 0.8=277m/s$$

This figure is much higher than the gas flow velocity of 5kWCO_2 laser in Japan as published in Hitachi Review, November 1982. The maximum gas flow velocity is 180m/s which is also higher than the gas flow velocity than a 20kW fast-axial-flow CO_2 laser as published in Japan in O plus E, September 1984. In this case, the gas flow velocity is 200m/s. Therefore, the author's high-speed wind tunnel successfully solved the gasdynamic problems of kilowatt-stage fast-axial-flow CO_2 lasers.

2. When the gap in the convergent section is 1.5 and 2.5cm, the gas filling pressure is between 20 and 30 torr, the motor input power is less than 12.5kW, and the pressure difference is smaller

TABLE 1

1 间隙	P充气(t) 2	P进(乇) 3	P出(乇) 4	△P(乇) 5	η	P总(乇) 6	P静(乇) 7	M	气体出口管温 8	9 输入功率 (kW)	泵温 10
	25.5	17	30.75	13.75	1.81	20	17	0.487		8.4kW	
无	30.75	21	36.75	15.75	1.75	26	23	0.422	15℃	9.5	20～30
12	19.5	14	23.25	9.25	1.66	16	13	0.552	44℃	6.8	
	28.65	12.375	37	24.625	2.989	20	11	0.965	45℃	11.5	
	23.25	10.125	28	17.875	2.765	15	9	0.886	37℃	10.7	
2.5 cm	20.4	9	24	15	2.667	13	7	0.9835	35℃	3.4	
	38.25	16.5	53	36.5	3.21	25	14	0.949	40℃	7.6	
	40.5	16.875	51	34.125	3.02	27	14	1.016	64℃	12.6	
	21.375	7.5	29	21.5	3.866	13	8	0.863		9	11
	25.5	8.4	32	23.6	3.809	13	8	0.863	35℃	9.6	开机10分钟35℃
1.5 cm	2[illegible].125	8.25	33	24.75	4	14	8	0.931	49℃	9.6	31℃
	30.75	10.125	43	32.875	4.25	20	11	0.965		13	
	27	9	39	30	4.333	17	9	0.998	47℃	11.6	15℃
	21.375	5.625	28	22.375	4.978	7	5	0.71		9.3	
	17.625	4.875	24	19.125	4.923	6	5	0.517	41℃	8	18℃
1cm	25.875	7.5	39	31.5	5.2	10	9	0.391		11.3	
	27.375	7.875	40	32.125	5.079	10	9	0.391	59℃	11.4	25℃
	30	8.625	21	32.375	4.75	11	13		54℃	11.8	

Remark: Gap is the spacing of ring-shaped nozzles in the convergent section; P_{exit} is the gas pressure at the pump exit; $\Delta P = P_{exit} - P_{inlet}$ $\eta = P_{exit}/P_{inlet}$; P_{inlet} = gas pressure at gas inlet of the pump; diameter of the experimental section of the high-speed wind tunnel is 80mm
KEY: 1 - Gap 2 - Gas filling 3 - P_{inlet} (torr)
4 - P_{exit} (torr) 5 - ΔP (torr) 6 - P_{total} (torr)
7 - P_{static} (torr) 8 - Tube temperature at gas exit
9 - Input power (kW) 10 - Pump temperature 11 - 35°C at 10 min after pump was started 12 - without

than 35torr, the mechanical pressure booster pump can operate satisfactorily.

TABLE 2

1 P进(mba)	2 P出(mba)	3 最大压缩比km	4 噪音测试结果
1	26.67	26.67	5 在极限真空时，距泵1米处四个方向上的噪音为：82.5dB,82.5dB,84dB,82.5dB
1.5	40	26.67	
3	57.33	19.11	6 环境噪音：45～46db
4.2	70.67	16.83	7 仪器：ND2型精密声级计倍频程滤波器
5	85.33	17.07	8 注：Km＝P出/P进 9 ZJ—1200泵的理论抽速为1650升/秒

KEY: 1 - P_{inlet} 2 - P_{exit} 3 - Maximum compression ratio km 4 - Results of noise test 5 - At highest vacuum, the noise levels in four directions, 1m from the pump, are: 82.5dB, 82.5dB, 84dB, and 82.5dB 6 - Environmental noise: 45 to 46db 7 - Instrument: model ND2 precision sound level meter and double-frequency filter 8 - Remark: Km = P_{exit}/P_{inlet} 0 - Theoretical suction rate of model ZJ-1200 pump is 1650 liters/s

3. To obtain the monomode output in a further step, the cross-sectional area of the electric discharge tube should be decreased. With a similar optical cavity length, to maintain constant output power of the device, the output power of a gas laser for a unit volume of mode should be increased. The most effective method of raising the output of unit volume of mode is to increase the gas flow velocity. Therefore, a high-pressure-difference gas-cooling mechanical pressure booster pump should be used. A model ZJ-1200 pump can be used only in kilowatt-stage CO_2 laser with low-order mode output. The gas-tightness performance and oil vapor phenomena of a pump operating for long periods of time are required to be improved.

4. In this experiment, air is used as the medium to simulate the flow characteristics of mixed gases in a CO_2 laser. In similar wind tunnels filled with CO_2 mixed working gases, the flow velocity is slightly higher than the flow velocity of air. In the following, the authors prove this with some calculations.

If the measured total pressure is 27torr and the static pressure is 14torr in a wind tunnel with air as the working medium, the adiabatic index of air is 1.4 if the temperature is calculated at 25°C.

From Eq. (2), the M number is calculated at 1.016. From Eq. (4), the local speed of sound is calculated at 346.11m/s. From Eq. (3), the gas flow velocity is calculated at v_{air}=351.64m/s.

If the same wind tunnel is used, by filling with CO_2 mixed working gas, the volumetric ratios of the gases are:

$$CO_2:N_2:He = 0.04:0.4:0.56$$

Then the adiabatic index of the mixed gas is 1.55 [3]. From Eq. (2), the M number is calculated as 0.9768. However, from Eq. (4), it is calculated that the local speed of sound is 364.183m/s, which is substituted into Eq. (3); the actual gas velocity can be calculated as

$$v_{mixture}=355.73\text{m/s}$$

By comparing the above results, $v_{mixture}>v_{air}$.

Therefore, the authors' simulated experiments have a theoretical basis with a practical value.

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